Three Monthly Meeting - Lausanne - April 2008

BIRG (EPFL B)
Crawling and Drumming

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Biologically Inspired Robotics Group (BIRG)
Ecole Polytechnique Fédérale de Lausanne (EPFL)

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Outline of the presentation

- General low-level control architecture based on Motor Programs (MP) and Pattern Generators (PG)
- Application to drumming iCub
- Locomotion specific design of pattern generators
- Sensory feedback for crawling

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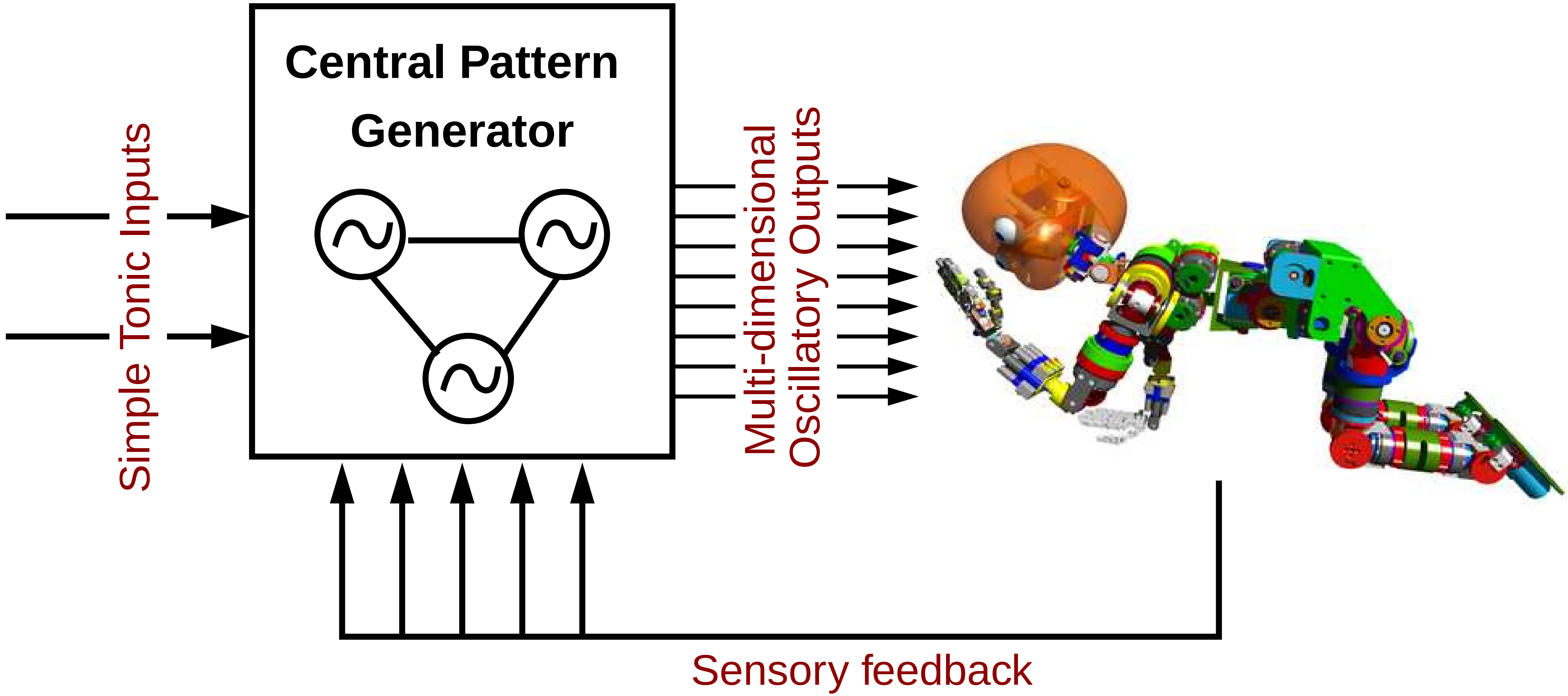
Pattern Generators in robotics



Pattern Generators in robotics

- Pattern Generators of movement primitives offer an interesting solution for robotic control
  $\Rightarrow$ reduction of the dimensionality of the control problem

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- Smooth modulation of the movement (speed, amplitude, position)
- Low-level feedback integration (with other CPGs, with the environment and/or with the body dynamics)
- They are modeled with dynamical systems

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Pattern Generator Based Architecture

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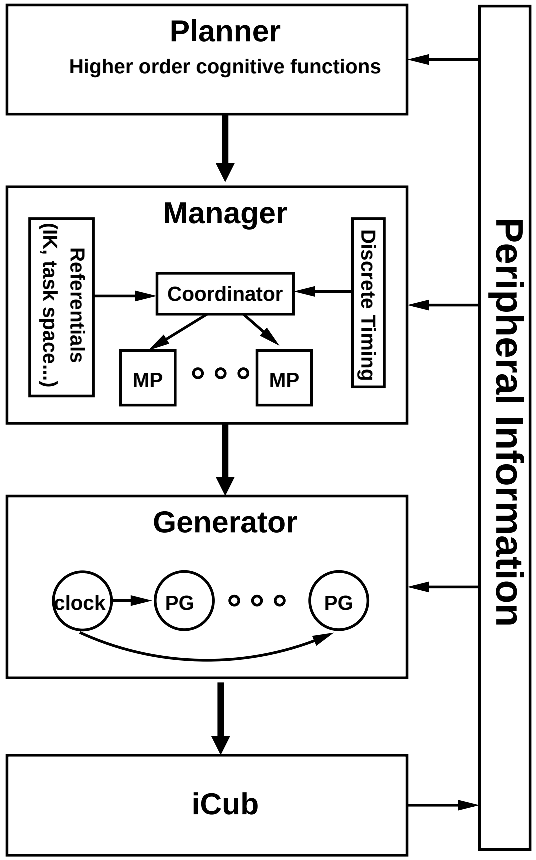
General control architecture

- We propose a three layered control architecture inspired by a functional model of the motor system
- At the Generator level there are several Pattern Generators (PGs) that generate complex coordinated movements
- Activation and coordination of these PGs is made at the Manager level, using Motor Programs (MPs) made of simple parameter sets
- This architecture is compatible with the iCub cognitive architecture, the planner corresponds to *prospection by action simulation*, the manager to the *modulation circuit* and the generator to the *phylogenetic self-organizing perceptuo-motor skills*



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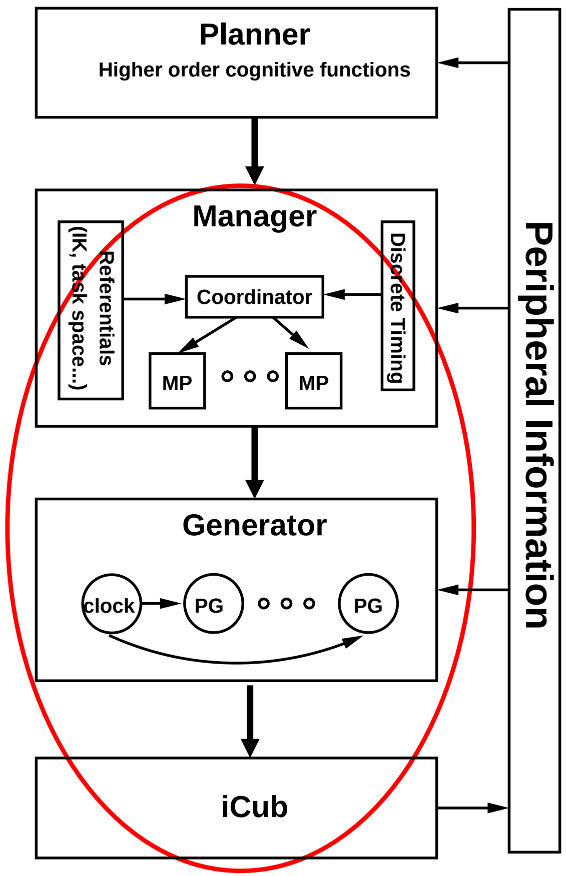

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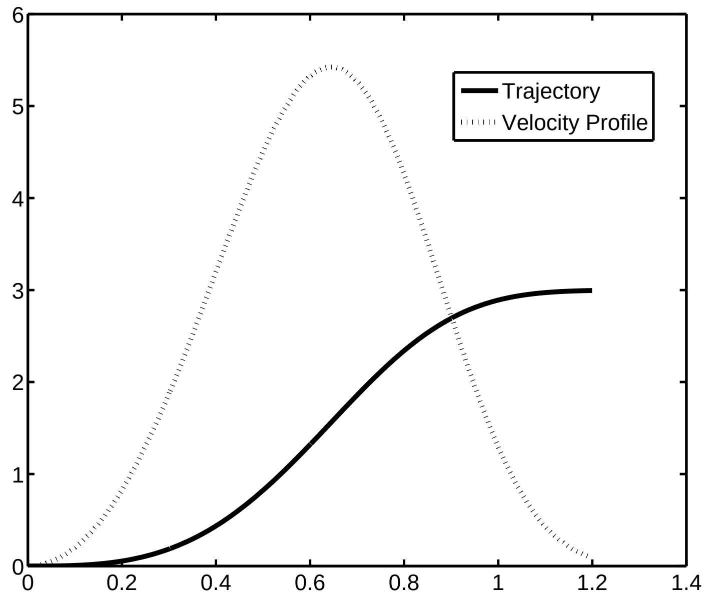
Discrete Pattern Generator

- Critically damped differential equation to generate a discrete trajectory
- Bell-shaped velocity profile
- Speed of convergence is controlled by b, point of convergence is controlled by g_i. These are the parameters controlled by the Motor Programs
- Valid for any initial positions since the ODE has a fixed point attractor

$$\begin{aligned}\dot{h}_i &= c(d - h_i)\\ \dot{y}_i &= h_i^4 v_i\\ \dot{v}_i &= d^4\,\frac{-b^2}{4}\,(y_i - g_i) - b\,v_i.\end{aligned}$$



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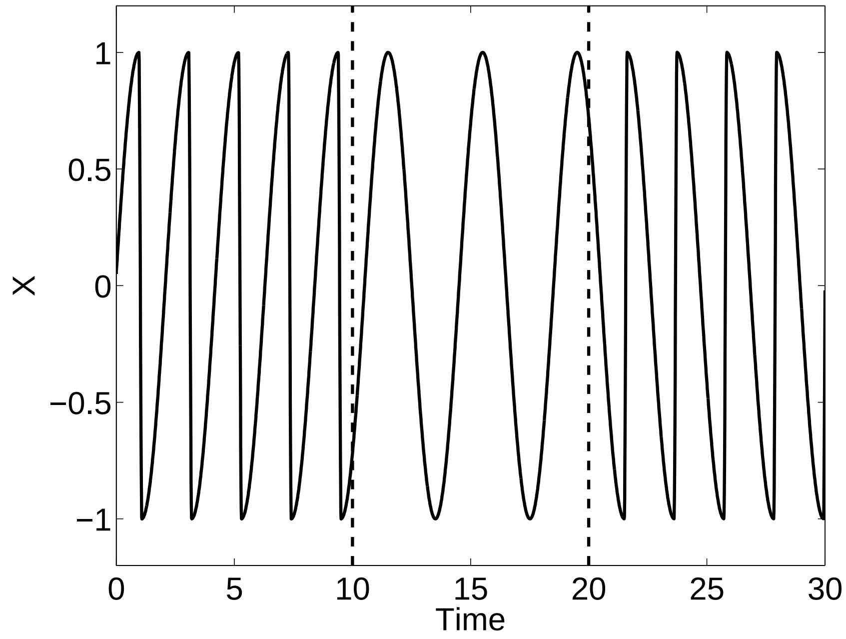
Rhythmic Pattern Generator

- Rhythmic movement primitive (when $m_i > 0$) that can be turned off via Hopf bifurcation ($m_i < 0$)
- Independent control of the ascending and descending phases of the oscillation
- The parameters controlled by the MPs are the frequencies ω_{down}, ω_{up}, and amplitude m_i of oscillations
- Valid for any initial positions since the ODE has a stable limit cycle

$$\begin{aligned} \dot{x}_i &= a\left(m_i - r_i^2\right) x_i - \omega z_i \\ \dot{z}_i &= a\left(m_i - r_i^2\right) z_i + \omega x_i \\ \omega_i &= \frac{\omega_{down}}{\mathrm{e}^{-bz_i}+1} + \frac{\omega_{up}}{\mathrm{e}^{bz_i}+1} \end{aligned}$$

where $r_i = \sqrt{x_i^2 + z_i^2}$



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Superimposition of movements

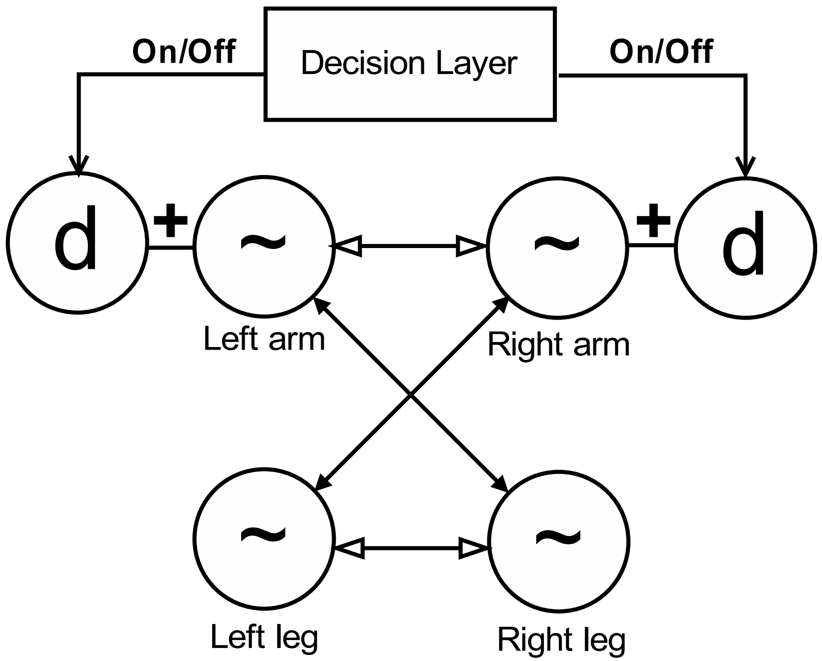
- We superpose the previous PGs by injecting the discrete movement into the rhythmic one

Discrete PGs

$$\dot{h}_i = c(d - h_i)$$
$$\dot{y}_i = h_i^4 v_i$$
$$\dot{v}_i = d^4 \frac{-b^2}{4} (y_i - g_i) - b\, v_i.$$

Rhythmic PGs

$$\dot{x}_i = a\left(m_i - r_i^2\right)(x_i - y_i) - \omega z_i$$
$$\dot{z}_i = a\left(m_i - r_i^2\right) z_i + \omega\,(x_i - y_i)$$
$$\omega_i = \frac{\omega_{down}}{e^{-bz_i} + 1} + \frac{\omega_{up}}{e^{bz_i} + 1}$$



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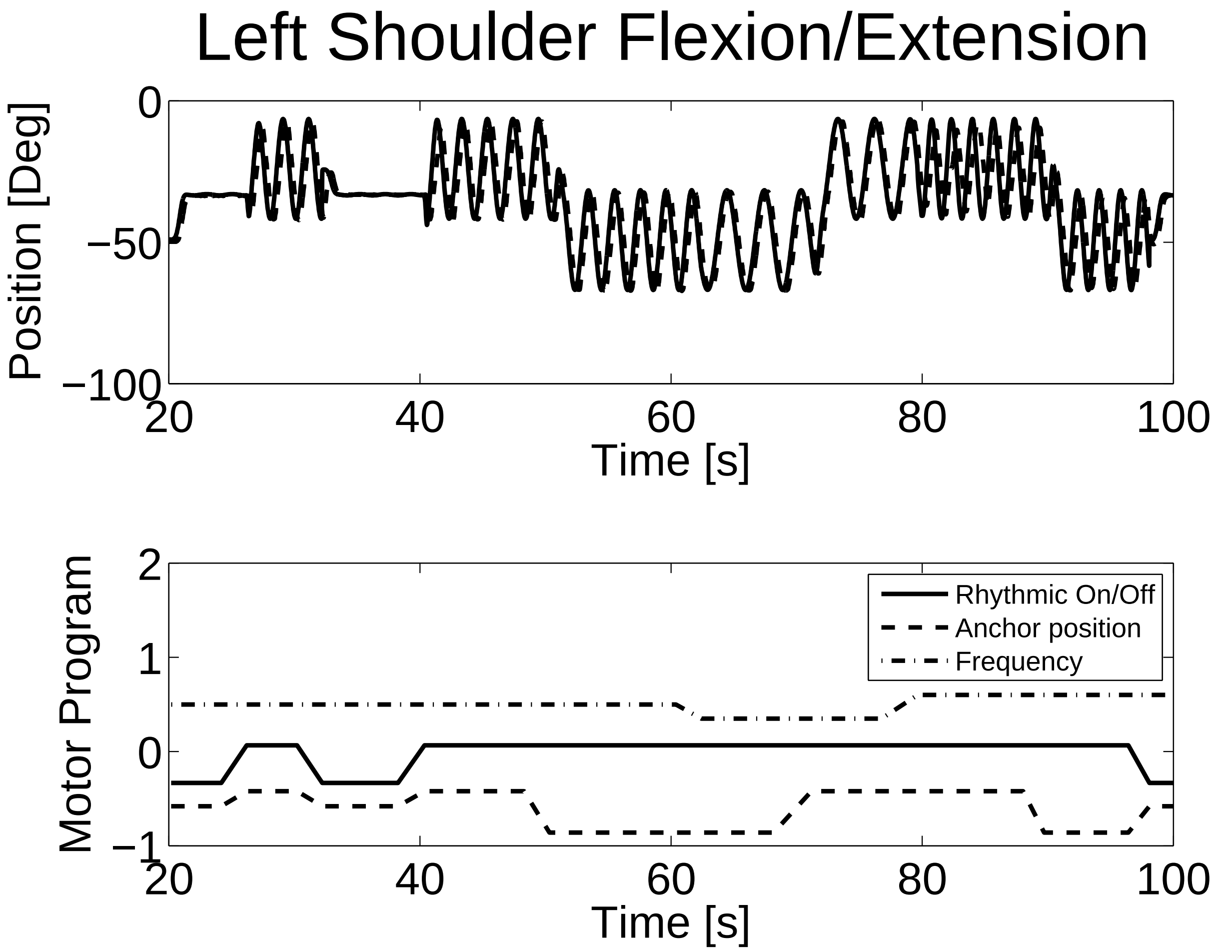
Example of trajectories (drumming)



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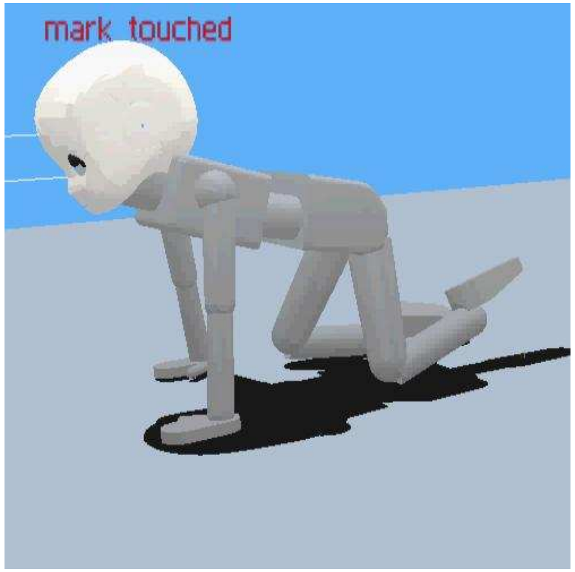
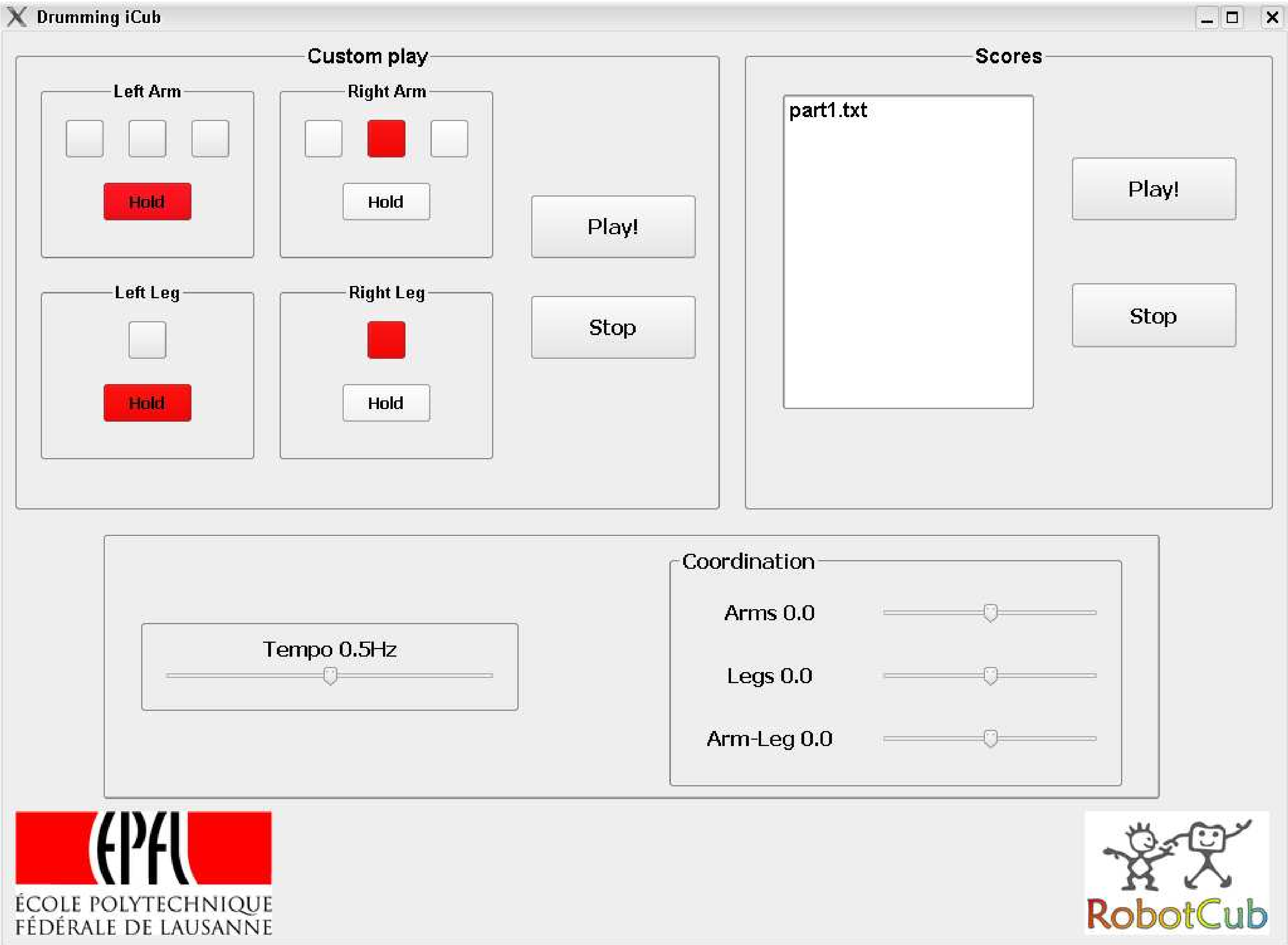
Applications to crawling and drumming



[Dégallier, Santos, Righetti and Ijspeert, Humanoids 2006]

[Dégallier, Righetti and Ijspeert, IROS 2007]


Drumming iCub
Custom play
Left Arm
Hold
Right Arm
Hold
Left Leg
Hold
Right Leg
Hold
Play!
Stop
Scores
part1.txt
Play!
Stop
Tempo 0.5Hz
Coordination
Arms 0.0
Legs 0.0
Arm-Leg 0.0
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Pattern Generators in the iCub

- Simple Motor Programs can generate complex and coordinated movements
- Implemented in Yarp modules that can easily be instantiated for each part of the body
- Could be used easily from any higher-level module
- Currently running on the PC104 of the iCub but could be moved to the DSPs (low computational cost)

Design of locomotion specific CPGs

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Context of locomotion

- We need locomotion specific pattern generators and feedback integration
- These CPGs should be general enough to be applied to very different legged robots
- Generation of different coordinated gaits
- Constant swing duration and stance duration related to speed of locomotion (as for all quadruped mammals including infants)
- Integration of sensory feedback compatible with observations from mammals
- Compatibility with the previous architecture

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Architecture of CPGs

- We present a generic way to construct networks of coupled dynamical systems able to generate any desired pattern of oscillation (i.e. gait)
- The design of the network is independent of the internal dynamics of each cell
- We use the theory of symmetric coupled cells network developed by Golubitsky et al.
- The analytic problem of finding ODEs such that the desired pattern of oscillations exists is transformed into an algebraic one (use of group theory)

[Righetti and Ijspeert, Robotics Science and Systems 2006]

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Symmetric coupled cells network

- Principle: design a network of dynamical systems that has the same symmetry group as the desired gait
- A symmetry in a coupled cells network is a permutation of the cells that preserves the architecture of the network (independent of the underlying ODEs)
- We distinguish 2 kinds of symmetries in sets of ODEs
  - Spatial symmetries γ are such that for any solution $x(t)$ we have $\gamma x(t) = x(t)$
  - Spatio-temporal symmetries φ are such that the orbits of $x(t)$ and $\varphi x(t)$ are the same (if $x(t)$ is a periodic solution then $\varphi x(t) = x(t + \psi)$)

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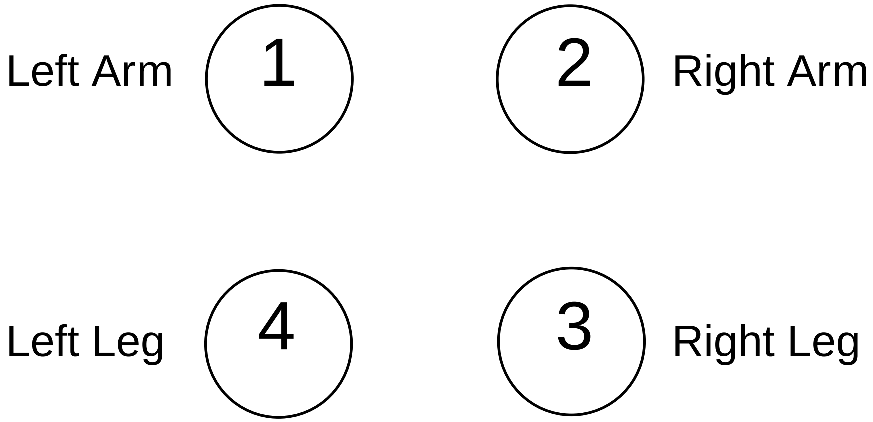
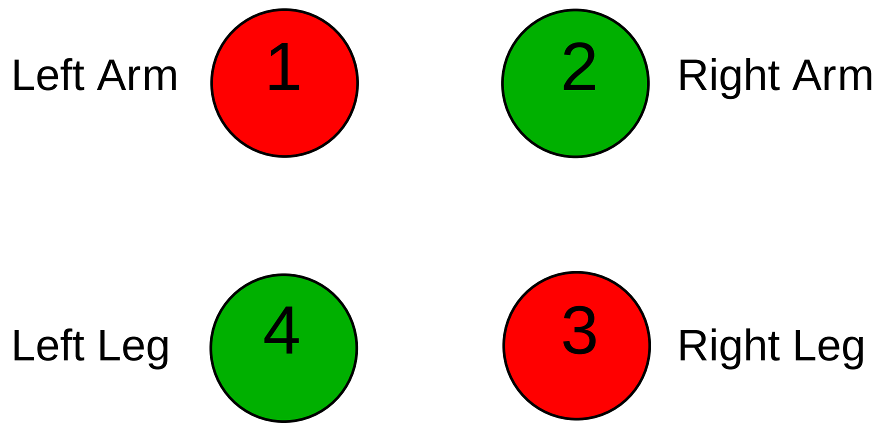
Example of symmetries



Trot-like gait
Diagonal limbs are in phase
Left and right limbs are half a period out of phase

Example of symmetries



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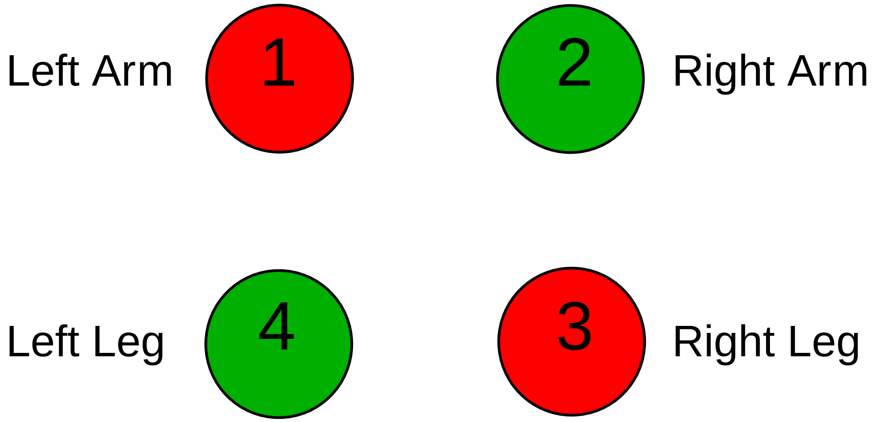
Example of symmetries



The trot gait has the following symmetries

$$\{(13)(24), 0\}$$
$$\{(12)(34), \frac{1}{2}\}$$
$$\{(14)(23), \frac{1}{2}\}$$

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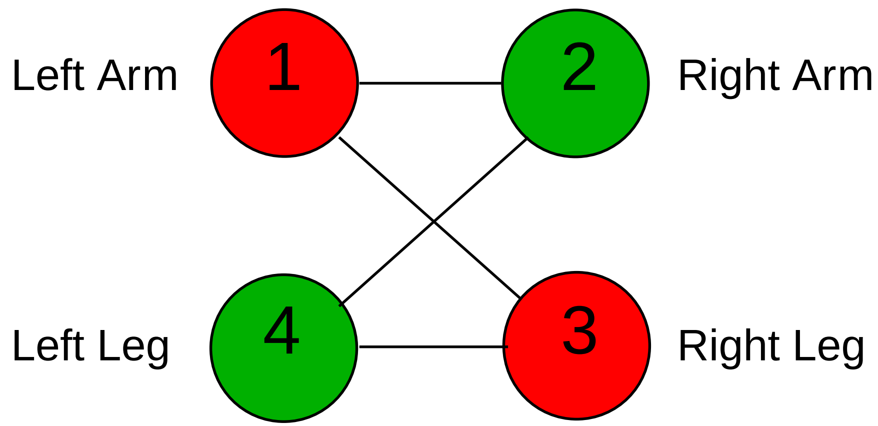
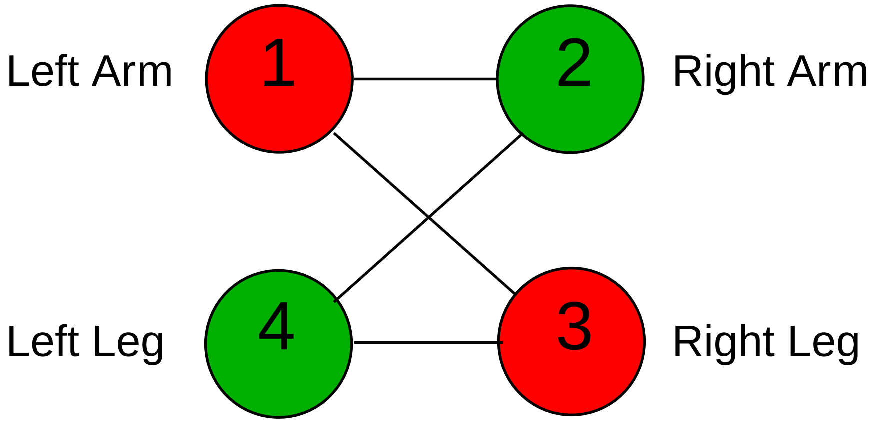
Example of symmetries



This coupling architecture has the same symmetry group
There exists periodic solutions with the trot symmetry

Example of symmetries



We find the other solutions of the network by calculating the subgroups of the symmetry group

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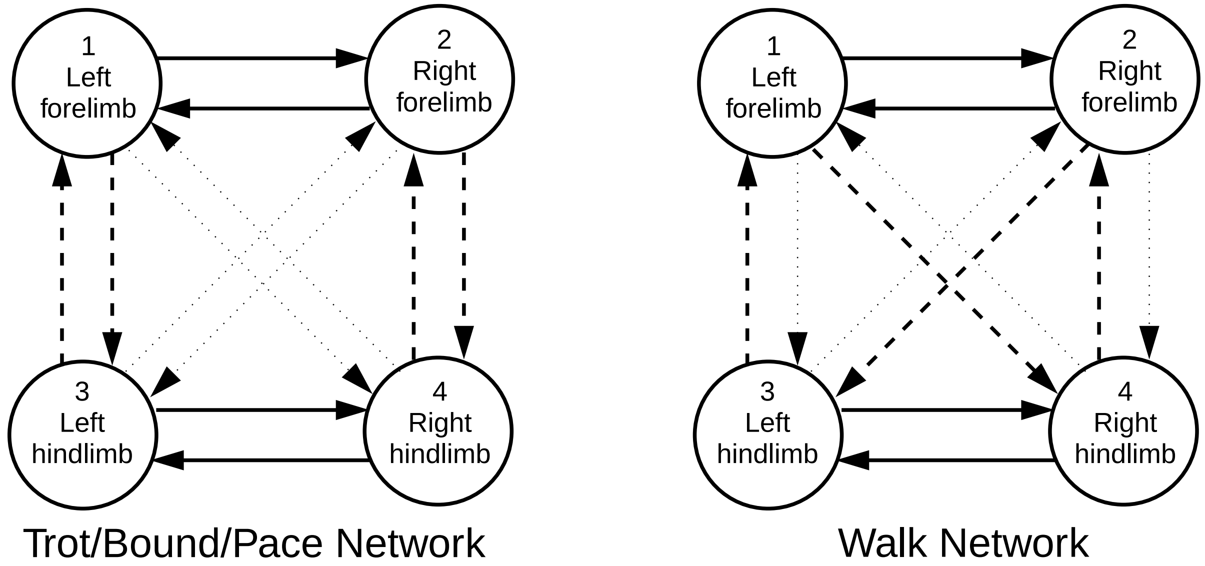
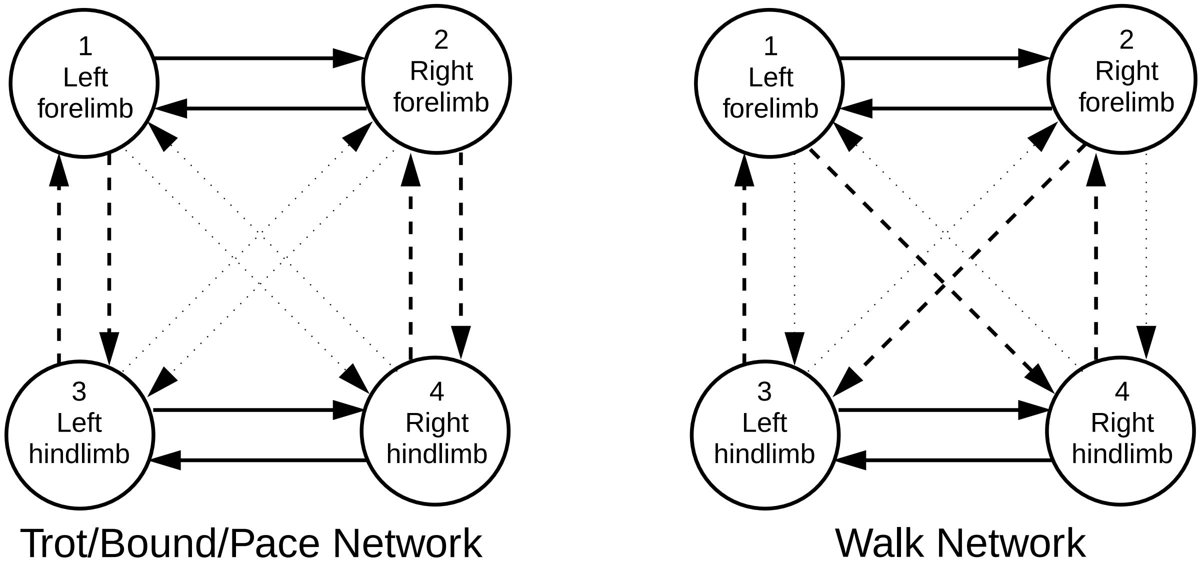
Generic CPGs



- Generic design of CPGs able to support the most common symmetrical gaits (walk, trot, bound and pace)
- The design is independent of the internal dynamics of each cell

Generic CPGs



- Generic design of CPGs able to support the most common symmetrical gaits (walk, trot, bound and pace)
- The design is independent of the internal dynamics of each cell

$\Rightarrow$ We can now design the dynamics of the cells

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Dynamics of the cells

- During locomotion, swing duration is constant, stance duration controls speed of locomotion
- However there is no oscillator in which we can independently control the duration of the ascending and descending phases of the oscillations (swing and stance)

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\begin{aligned}
\dot{x}_i &= \alpha(\mu - r_i^2)x_i - \omega y_i \\
\dot{y}_i &= \beta(\mu - r_i^2)y_i + \omega x_i
\end{aligned}
$$

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\omega &= \frac{\omega_{stance}}{e^{-by}+1} + \frac{\omega_{swing}}{e^{by}+1}
\end{aligned}$$

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\begin{aligned}
\dot{x}_i &= \alpha(\mu - r_i^2)x_i - \omega y_i \\
\dot{y}_i &= \beta(\mu - r_i^2)y_i + \omega x_i + \sum k_{ij} y_j \\
\omega &= \frac{\omega_{stance}}{e^{-by} + 1} + \frac{\omega_{swing}}{e^{by} + 1}
\end{aligned}
$$

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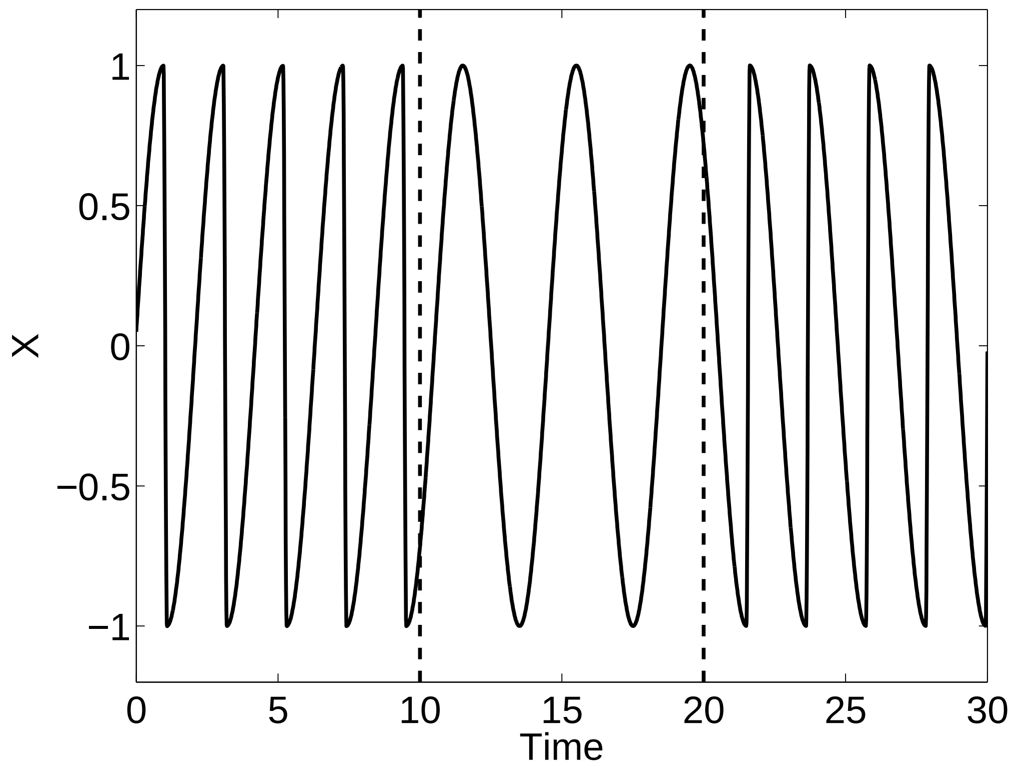
Dynamics of the cells



- By changing ω_{swing} and ω_{stance} we can independently control the duration of the ascending and descending phases of the oscillation (i.e. we control the duration of swing and stance phases)

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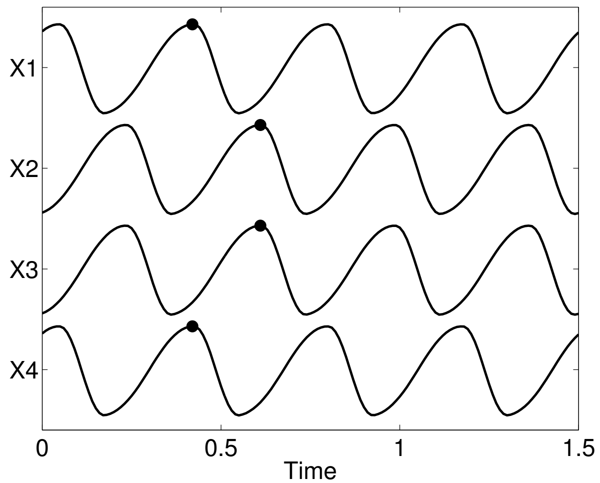
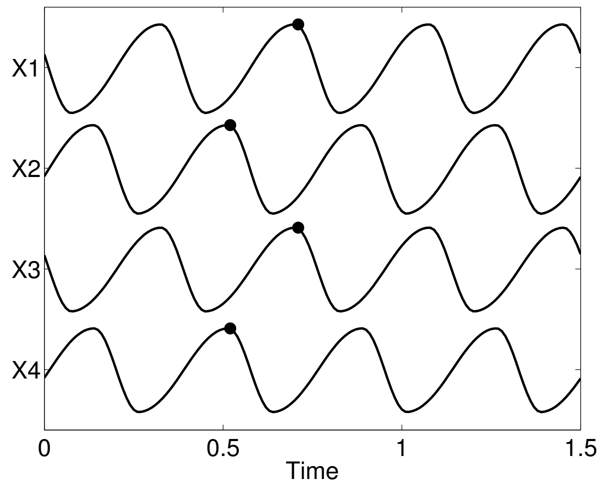
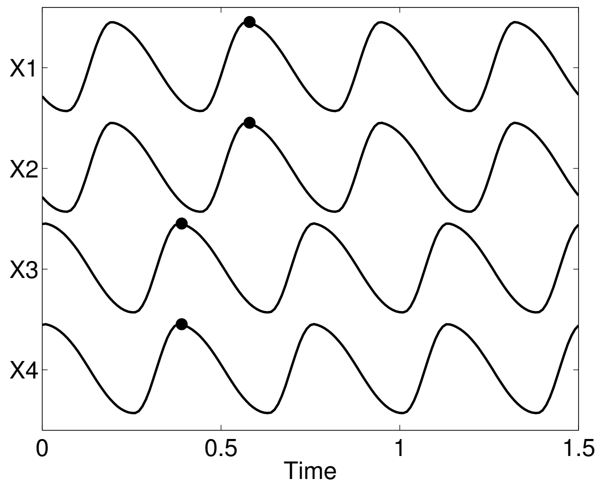
Gait generation



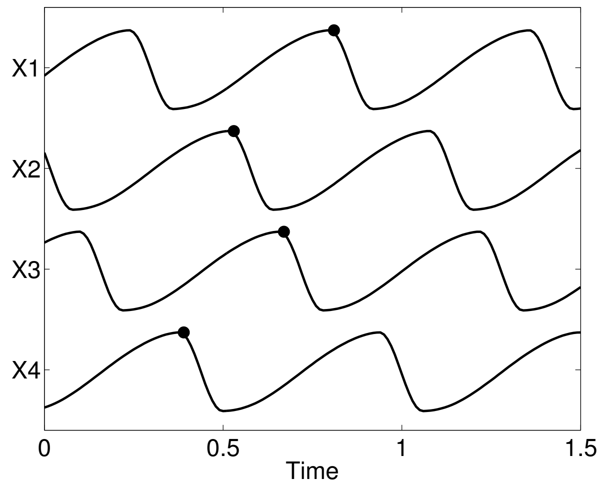
Trot



Pace



Bound



Walk

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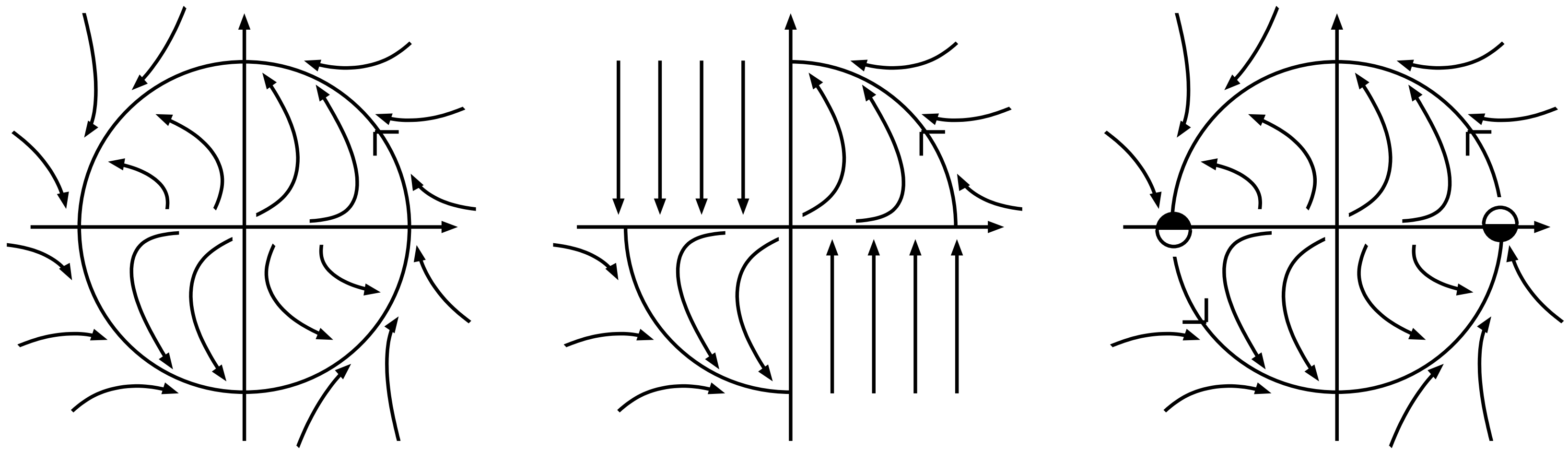
Sensory feedback

- The integration of sensory information at the CPG level is phase dependent during animal locomotion
- Transitions between swing and stance phases are critical
- Sensory feedback strongly couples the neural controller with the system it controls
- We design phase dependent sensory feedback in such a way that it explicitly shapes the dynamics of the oscillators
  "the CPG is controlled by the mechanics"

[Righetti and Ijspeert, ICRA 2008]

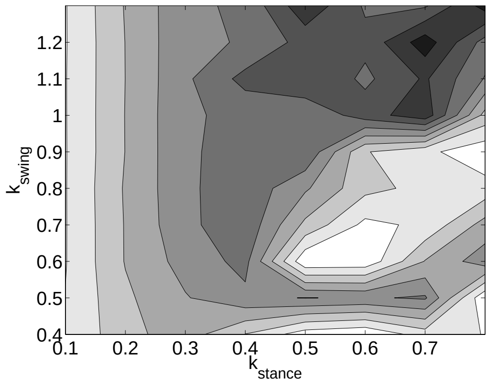
Sensory feedback integration



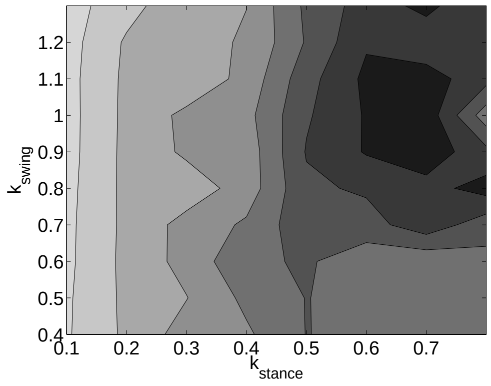
$u_i = 0$ | $u_i = \pm F$ | $u_i = -\omega x_i - \sum k_{ij} y_j$

$$\begin{aligned}
\dot{x}_i &= \alpha(\mu - r_i^2)x_i - \omega y_i \\
\dot{y}_i &= \beta(\mu - r_i^2)y_i + \omega x_i + \sum k_{ij} y_j + u_i \\
\omega &= \frac{\omega_{stance}}{e^{-by} + 1} + \frac{\omega_{swing}}{e^{by} + 1}
\end{aligned}$$

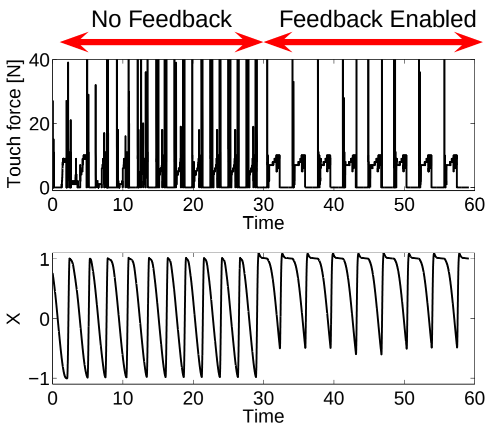
Sensory feedback integration

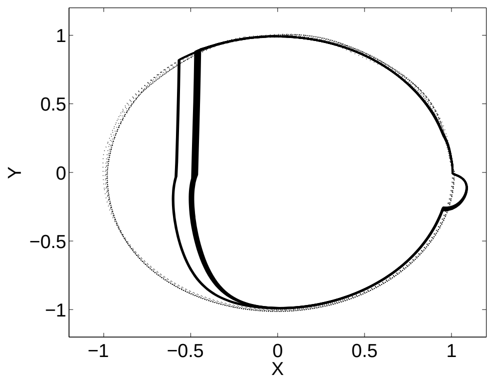


Speed no feedback



Speed with feedback





- Tests where performed with 3 different simulated robots, from rigid ones to ones with passive dynamics
- In all simulations, speed is independent of swing duration and correlated to stance duration as in mammals!
- With the feedback, locomotion is more robust to parameter uncertainty
- The robots can locomote on uneven terrains and slopes
- The controller is tightly coupled to the robot and its environment (mutual entrainment)
- The **same controller** works for different kinds of robots and gaits (e.g. walk and trot with the Aibo, walk and bound with a robot with passive dynamics)

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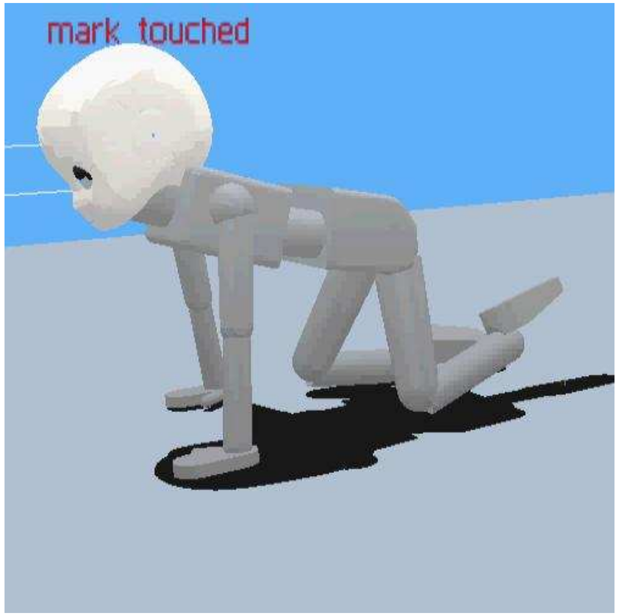
Integration in the general architecture

Generation of different behaviors using the same Pattern Generators with different Motor Programs

- Crawling
- Reaching while crawling
- Crawling then reaching



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Conclusion

- We developed a modular architecture based on Pattern Generators and Motor Programs
- Any higher-level cognitive function could use this framework by simple parameter specifications to the Pattern Generators (goal, speed, frequency...)
- Complete integration as modules in Yarp, successfully tested on the iCub for drumming
- Locomotion specific sensory feedback was successfully integrated

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